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Erosion Testing of Coatings for V-22 Aircraft Applications

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Abstract

High velocity (600'/s) sand erosion tests in a wind tunnel were conducted to evaluate developmental coatings from 3 separate companies under Navy phase I SBIR program funding. The purpose of the coatings was to address a particular problem the V-22 (Osprey) tilt-rotor aircraft was having with regards to ingestion of sand particles by a titanium impeller that was associated with the aircraft environmental control system. The three coatings that were deposited on titanium substrates and erosion tested included: (1) Si_xC_y/DLC multilayers deposited by CVD, (2) WC/TaC/TiC processed by electro-spark deposition, and (3) polymer ceramic mixtures via an aqueous synthesis. The erosion test results are presented, which provided the basis for assessing the suitability of some of these coatings for the intended application.

Introduction

The Navy's V-22 tilt-rotor aircraft uses a shaft driven compressor (SDC) to supply compressed air to the environmental control system (ECS), the on board oxygen generation system (OBOGS), and the wing de-icing system. These compressors require high-speed (100,000 rpm) impellers for air intake and are equipped with particle separators to prevent abrasive particles contained in the airstream from contacting the titanium impeller. Low altitude operations in helicopter mode over sandy/dusty environments have resulted in an overtaxed particle separator and rapid wear of the impeller fins causing significant performance reductions

and in some cases catastrophic failures of the impellers. This paper reports the results of a small business innovative research (SBIR) program solicited by the U.S. Navy[A] and awarded to three companies with unique coatings/surface treatment approaches.

Three types of coatings were deposited on a Ti-6Al-4V base alloy by 3 different techniques and vendors selected in the Phase-I SBIR program. The three coatings that were deposited included: (1) SiC/DLC multilayers deposited by CVD, (2) WC/TaC/TiC processed by electro-spark deposition, and (3) polymer ceramic mixtures applied via an aqueous synthesis route. Each of these coating systems were optimized and applied to the Ti-based substrates, and some of their properties relevant for protection against erosion were measured, which included erosion tests in a wind-tunnel *[1]*. The erosion resistant coatings must possess certain attributes in order to protect the substrate and the process of their deposition should be benign enough not to degrade the substrate materials. Some of these attributes include strong adhesion to the substrate, hard and aerodynamically smooth coating, high fracture toughness, low internal state of tensile residual stress, low temperature processing to maintain substrate metallurgy, conformal coating methods, and a low erosion rate to significantly extend the product life cycle. Results obtained from the wind-tunnel tests for each of the coating systems are presented in this paper, which are then used to assess their potential for erosion protection of Ti-based substrate materials. These initial findings are then used to downselect promising coating systems for further development in the Phase-II SBIR program.

[A] NAVAIR, Aerospace Materials Division, Patuxent River, MD.

Experimental Procedures and Results

(a) Si_xC_y/DLC multilayers deposited by CVD [2]

A coating of DLC (Diamond Like Carbon) with the trade name Ultra C was deposited on Ti-6-4 coupons of 1"x1" size using a low temperature (<150°C) CVD process by Surmet Corporation. The details of the coating process are not available, but a multilayered coating consisting of 25 alternate layers each of an amorphous Si_xC_y and DLC were deposited on the substrates. Advantages of the multilayered concept is to provide high fracture toughness, low internal stresses, and the ability to control both the total stress in the coating and a (positive) compressive stress at the coating surface. Changes to the individual layer thickness and numbers of alternating layers were made to study the effects on selected properties to obtain an optimized coating system.

Coated samples were characterized by adhesion tests using ASTM D3359-97 standard. In this test a scratch was made and a 3-M tape was bonded to the coated surface and peeled off. This test indicated no removal of the coating by the tape, which was an indication of excellent adhesion. Erosion tests were initially conducted at University of Dayton (UD), where they regularly perform dust erosion tests for (aircraft) cockpit canopies and mostly monitor the changes in transmission as a result of scratching the window. These conditions were too mild to simulate the level of erosion that was typical for the titanium impeller. Consequently, erosion tests were done in a wind tunnel facility at the University of Cincinnati (UC) using Arizona dust with silica particle sizes between 10-100 μm and 9.5μm alumina at particle velocities of 600'/s. The initial set of samples with just the DLC (UltraC) coating did not survive but the multilayered

(nanolaminated) coating consisting of Si_xC_y/DLC displayed very good erosion resistance. A summary of test results is given in Tables 1 and 2.

Friction and wear tests were also conducted to gauge the performance of these coatings on Ti-based substrates. Pin-on-disc tests were performed in which the Ti-based disc was coated with different coatings and the pin was either an alumina or silicon nitride ball. The test with alumina was done at a load of 10N and for silicon nitride a load of 15.68N was used. Tests were done at 71 rpm and a linear speed of 10 cm/s. The results of the wear tests are given in Table 3. It is apparent that the layered coating, designation C, displayed superior wear performance, which is consistent with the erosion test results. The hardness and elastic modulus of the layered coatings was reported as 25.8 GPa and 206 GPa, respectively. In addition, the CVD multi-layer coating process demonstrated excellent ability to coat complex shapes on an actual impeller as shown in Fig.1. It should be noted that this impeller had seen time in a compressor prior to coating as evidenced by the rounded impeller blade tips.

(b) WC/TaC/TiC Processed by Electro-Spark Deposition [3]

In this program WC-TaC-Co and WC-TiC-Co coatings were deposited on Ti-based substrates using the Electro-Spark Alloying (ESA) approach shown in Fig. 2 by Surface Treatment Technologies, Inc. The process uses an electrode of the coating material, which gets deposited on the substrate by a micro-welding process as the electrode is rastered over the substrate. Initial tests utilized coatings of WC-TaC-Co, WC-TiC-Co, Cr_3C_2-Ni, TiC-Ni-Mo, TiB_2, and the baseline Ti-alloy. An in-house erosion test was used to assess initial performance of these coatings. These tests were done using 50 μm alumina particulate at 500ft/s, 30° and 90° incident angles, and with particle loading of 12g/min. The tests were done for a relatively short

time of 1 min. The results of these tests are given in Figs. 3 and 4 and show higher erosion rates for tests done at 30° angle than at 90°. None of the coating breached and two of the best performing coatings, based on WC-TaC-Co and WC-TiC-Co, were further evaluated for 3-minute duration with good results.

Additional independent erosion testing was conducted in the wind tunnel at UC. These tests included WC-TaC-Co and WC-TiC-Co coatings of 0.002" thickness. This first set of coatings showed excessive wear in tests done at UC. Similar tests done by UC on another set of re-engineered coatings showed improved erosion behavior but not sufficient to the extent shown by the other coating methods. The coating process was also demonstrated on an impeller, however, feedback from the impeller manufacturer[B] indicated the surface roughness resulting from the ESD coating process was not desirable for this high-speed aerodynamic component.

(c) *Polymer-Ceramic Coatings Applied via an Aqueous Synthesis Route [4]*

The coating concept pursued by Analytical Services and Materials, Inc (AS&M) consisted of a mixture of nanoscale ceramic particles (e.g. silicon nitride, titanium di-boride, etc.) in a specially formulated polymer matrix to protect the Ti-based materials from erosive wear. The basis of the AS&M approach was that a hard ceramic coating wears more at 90°-impingement angle and a soft metallic coating at low impingement angles (e.g. 30°). Therefore, a mixture of a soft polymer matrix containing hard ceramic particles in a composite coating may offer superior protection for this impeller application.

Initial test results were done on a variety of coating systems with different combinations of ceramic powder and polymer to determine the relative erosion rates, adhesion of coatings to the substrate, and the effect of the coating processing on fatigue behavior of the Ti-based

[B] Honeywell Engine Systems, Torrance, CA

substrate material. Based on these results a number of promising coatings were tried in the Phase-I SBIR program. Figure 5 shows the results of in-house erosion tests of uncoated and coated samples exposed to Arizona dust, alumina, and silica particles. Coatings with series MCS and ECN appear promising and show particularly low erosion rates. Coatings containing hard ceramic particles in a resilient polymer matrix provided the lowest erosion rates. Figure 6 gives a summary of the adhesion test results (Hesiometer) on these coatings. Some of the coatings such as GNH C show unusual adhesion, which was enhanced by adhesion promoters.

Promising coatings were further optimized for the type and the amount of the filler and their influence on the erosion rate. The erosion behavior of the coated substrates was compared with the erosion behavior of the uncoated base metal and with a WC-Co plasma sprayed coating. Generally, matrix materials affected the erosion rate more than the type of the ceramic filler, and glancing angle erosion rate was greater than for normal incidence. The more resilient matrix coatings gave the lowest erosion rates.

Figure 7 shows erosion rates for the ECN-A coating, which is based on a resilient polymer. Good erosion rates were obtained for filler levels up to ~40%. Also shown are data for the bare substrate and WC erosion rates. Other batches from the ECN class of coatings were also tested for erosion rates as summarized in Fig. 8. The data show that some of the coating compositions (ECN-I, ECN-H) can produce low erosion rates at higher filler loading than for coating composition ECN-A. Another promising coating class, MCS, with resilient matrix was investigated. The results are summarized in Fig. 9, which show very low erosion rates, even lower than the WC coating data. Another coating class, GNY, showed results between ECN and MCS coatings.

Table 5 gives a summary of the erosion rates for each of the coatings based on the erosion tests performed at University of Cincinnati. Although the actual erosion rate may depend on the

test conditions and the particular history of the sample, it is apparent that in general multilayered Si_xC_y/DLC coatings showed the lowest erosion rate followed by polymer-ceramic coatings. The coatings of WC-TaC-Co and WC-TiC-Co showed the highest erosion rates among the 3 coatings investigated.

Conclusions

Three types of coatings were evaluated for high velocity sand erosion behavior in a U.S. Navy Phase-I SBIR program. The coatings were multilayered Si_xC_y/DLC deposited by CVD, WC-TaC-Co and WC-TiC-Co processed by Electro-Spark Alloying, and Polymer-Ceramic composites coating synthesized by a liquid coating method. Each of these coatings was deposited on Ti-based substrates and erosion tested in a wind tunnel facility at University of Cincinnati. The preliminary results showed superior performance for the multilayered Si_xC_y/DLC and polymer-ceramic coatings in comparison to the coatings deposited by Electro-Spark Alloying method.

Acknowledgments

The authors gratefully acknowledge the support of the NAVAIR Science & Technology Office, the V-22 program office and the Office of Naval Research for supporting this effort.

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Table 1. Erosion test results on nano-laminated Si_xC_y/DLC coating structure using Alumina particles (9.5μm) at 600'/s.

Angle of Impact (°)	Mass Loading (g)	Erosion Rate (mg/g)
90	5	0.092
90	5	0.074
90	20	0.05
90	30	0.03
90	100	0.03
	160 (TOTAL)	.0552
30	10	0.270
30	50	0.60
30	20	1.11
30	20	1.4
	100 (TOTAL)	0.845

Table 2. Erosion test results on nano-laminated Si_xC_y/DLC coating structure using silica particles (100-200μm) at 600ft./s.

Angle of Impact (°)	Mass Loading (g)	Erosion Rate (mg/g)
90	100	1.76
90	100	1.10
	200 (TOTAL)	1.43

Table 3: Wear volume for different samples of Si_xC_y/DLC.

Sample* ID	Wear volume (mm^3) at 10 N	Wear volume (mm^3) at 15.68N
A	NMW	0.02058
B	NMW	0.02252
C	NMW	0.01355
D	4.1134	-
E	6.8606	-

NMW = No measurable wear. *The samples tested were: Sample A: 2μm thick UltraC Diamond Hard Carbon Coating, Sample B: 15μm thick SiC + 2μm thick UltraC Diamond Hard Carbon Coating, Sample C: Layered Structure (SiC and UltraC) Total-6 layers, Sample D: SiC 15 μm thick, Sample E: Bare Ti Alloy

Table 4: Wind tunnel erosion test results on WC/TaC/TiC samples tested at UC

Alumina (9.5 μm), 90°, 600'/s:	
WC-TiC-Co	0.156 mg/g
WC-TaC-Co	0.184 mg/g
Arizona Road Dust (1-100 μm), 90°, 600'/s:	
WC-TiC-Co	2.3 mg/g
WC-TaC-Co	2.95 mg/g

Table 5: A summary of erosion rates of three types of coatings tested at University of Cincinnati in the SBIR program.

Company	Sample	Erodent, Angle, Mass	Erosion Rate (w/g)	Remarks
Surface Treatment Tech., Inc	7473(12)	9.5 µm Al_2O_3,30°, 5g	1.206	Uncoated Baseline-Ti
"		SiO_2 Arizona Dust, 90°, 10g	2.3	"
"		100-200 µm, SiO_2, 90°, 100g	1.8	"
"	7422 (1)	9.5 µm Al_2O_3 , 90°, 5g	0.16	Coated-WC-TiC-Co
"	7422 (7)	9.5 µm Al_2O_3 , 30°, 5g	0.49	Coated- WC-TiC-Co
SURMET	5	9.5 µm Al_2O_3 , 90°, 5g	0.092	DLC/SiC multilayer
"		9.5 µm Al_2O_3 , 30°, 5g	0.6	DLC
AS&M	KRET 134 (8)	9.5 µm Al_2O_3 , 30°, 10g	0.045	Polymer, 37 w/o Si_3N_4
"	"	100-200 µm, SiO_2, 90°, 100g	0.054	"

List of Figures:

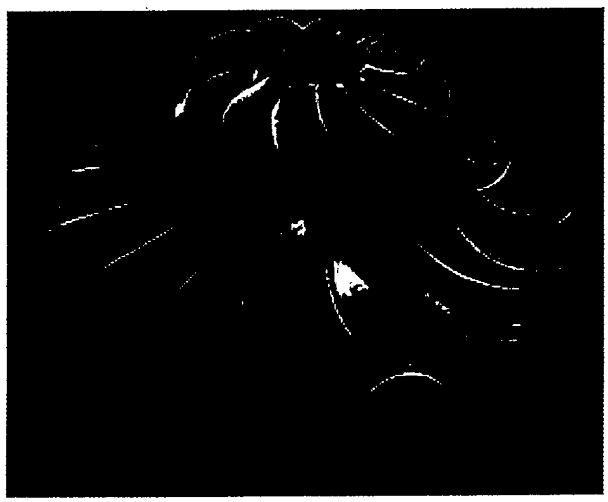

Fig. 1 Photographs of a scrap SDC titanium alloy impeller (taken from Service) coated with SURMET's hard carbon erosion resistant coating.

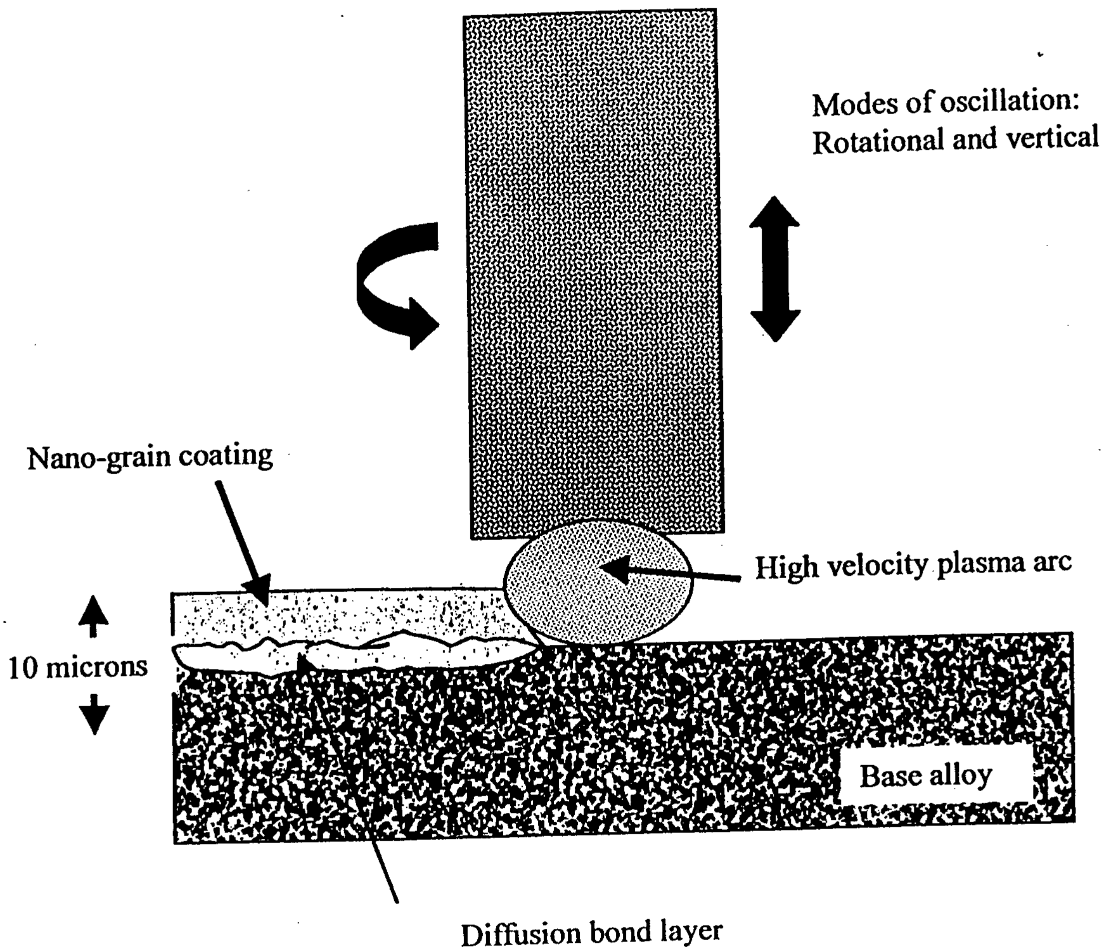

Fig. 2. Schematic of the ESA process showing the electrode transfer into the bulk alloy.

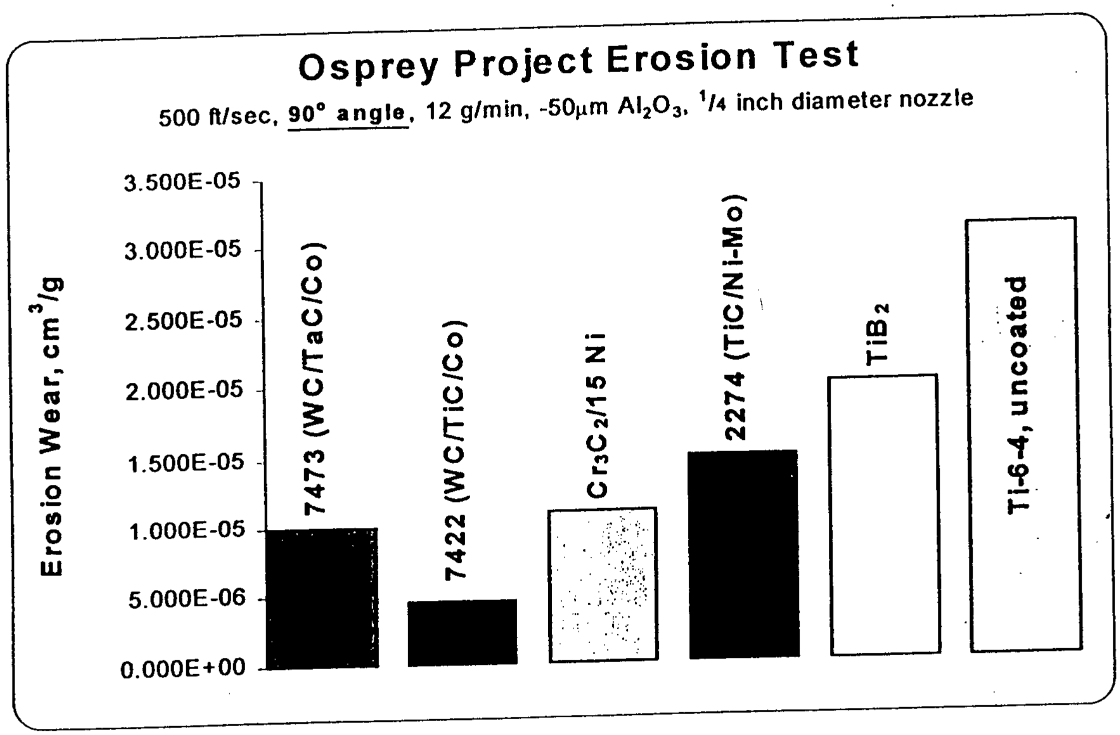

Fig. 3. Results of the 1-minute erosion test at 90° impact angle.

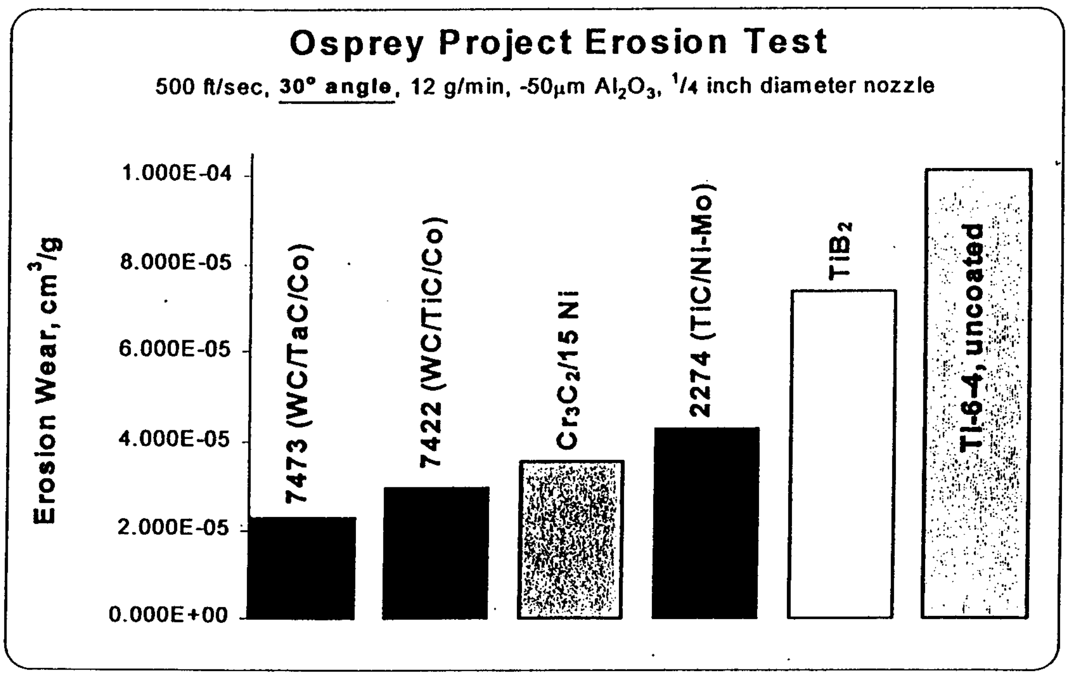

Fig. 4. Results of the 1-minute erosion test at 30° impact angle.

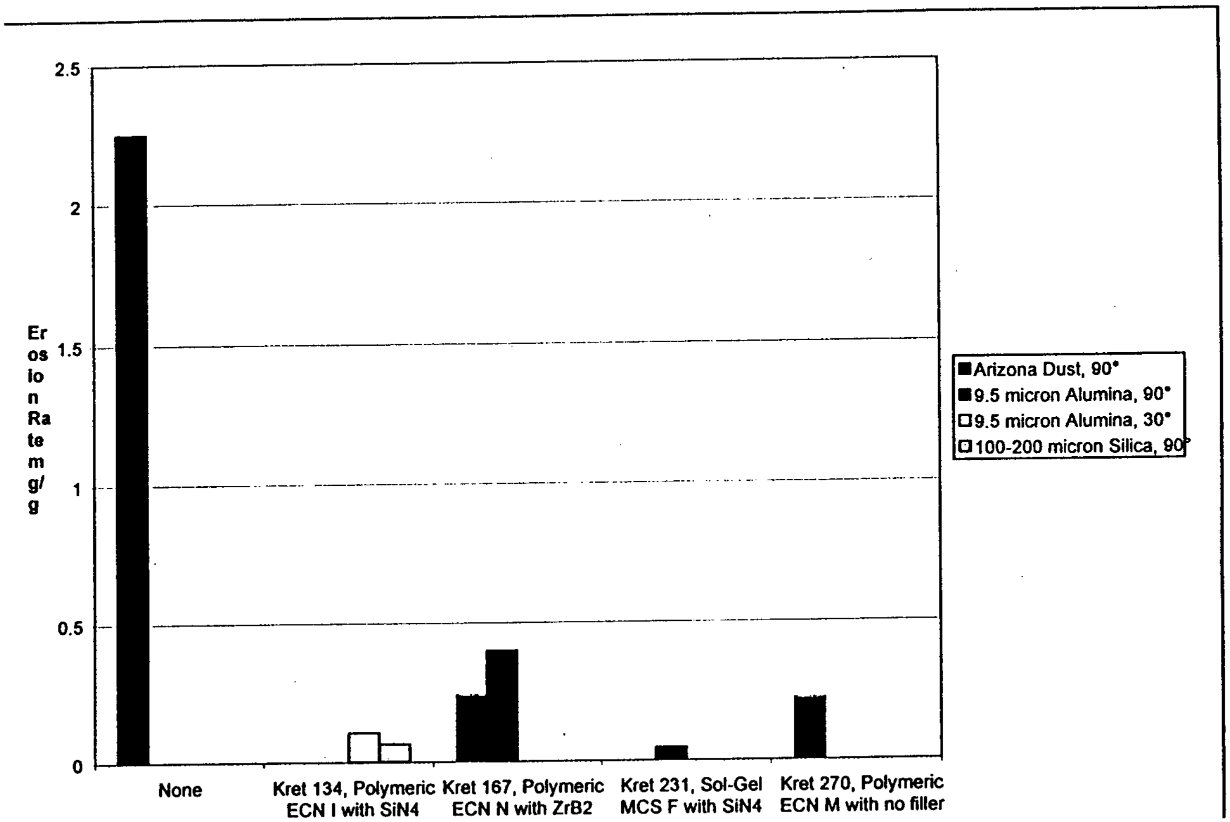

Fig. 5. Erosion rates measured at University of Cincinnati in tests at 600'/s (183 m/s).

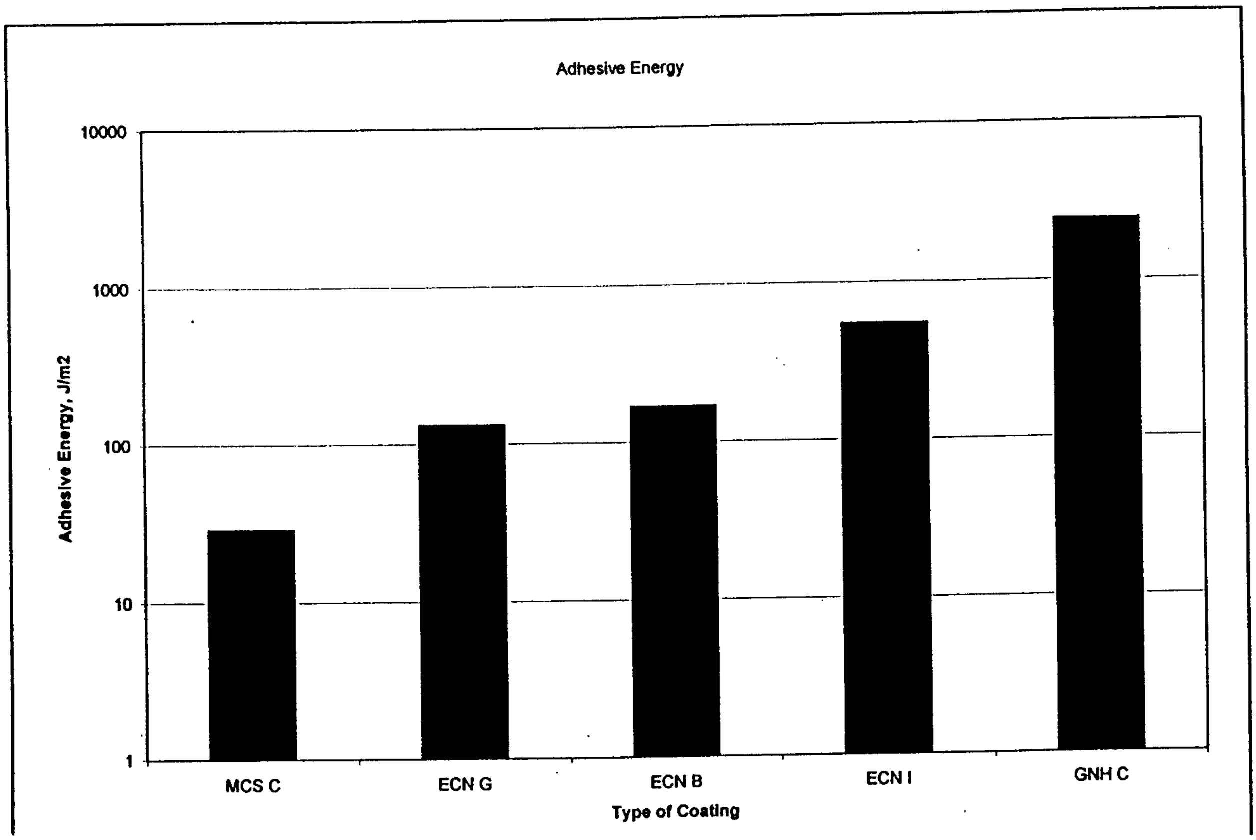

Fig. 6. Hesiometer adhesion test results from different coatings.

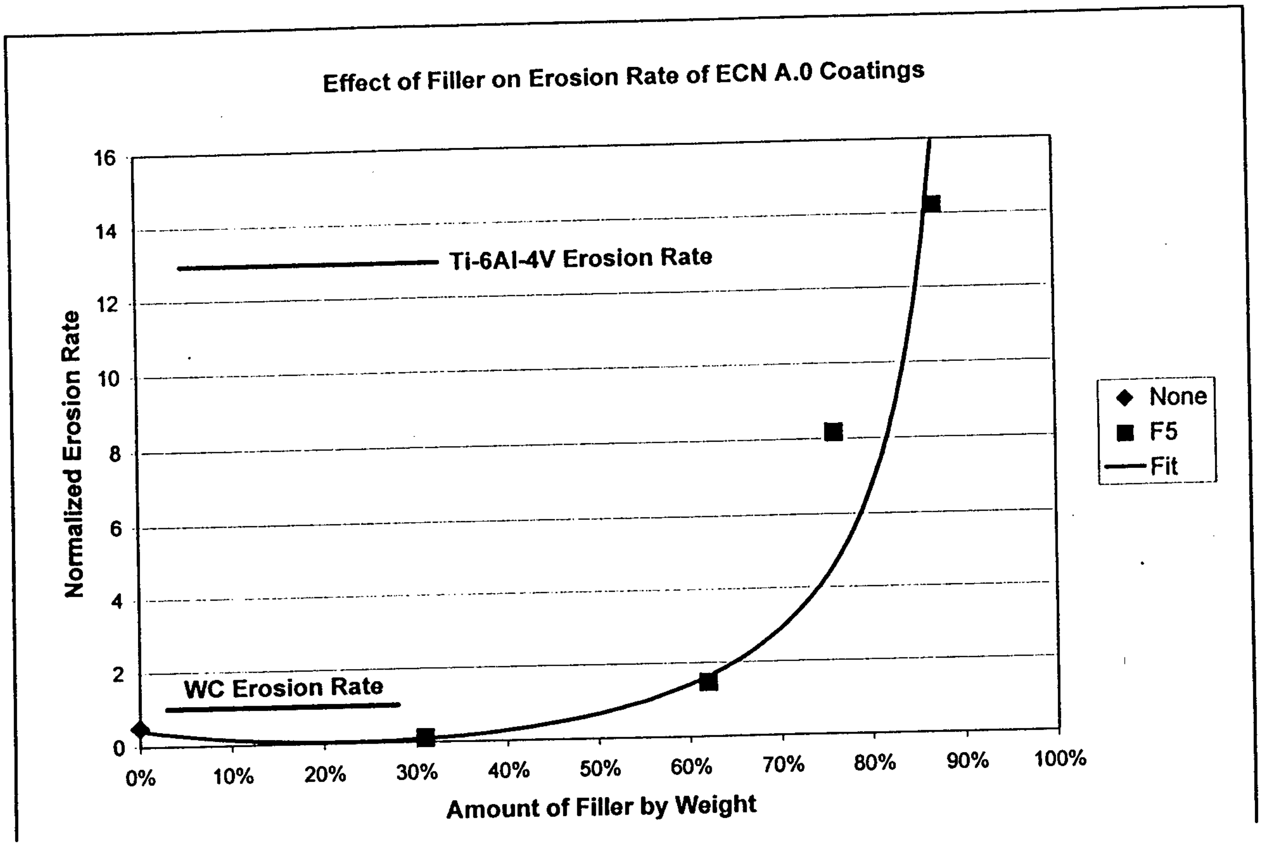

Fig. 7. Effect of filler on erosion of ECN-A coatings.

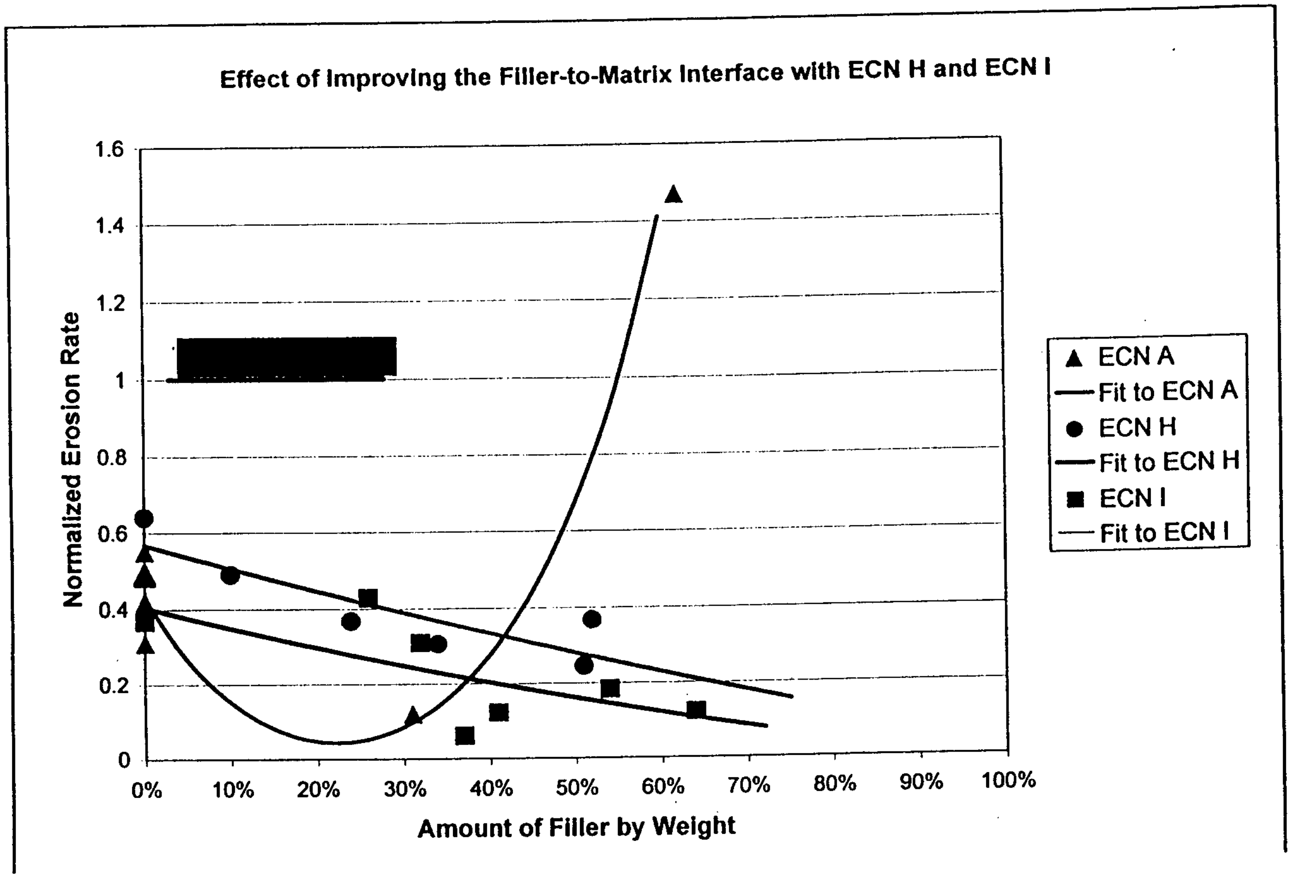

Fig. 8. Effect of improved filler-to-matrix interface in ECN-H and ECN-I coatings on the erosion rate.

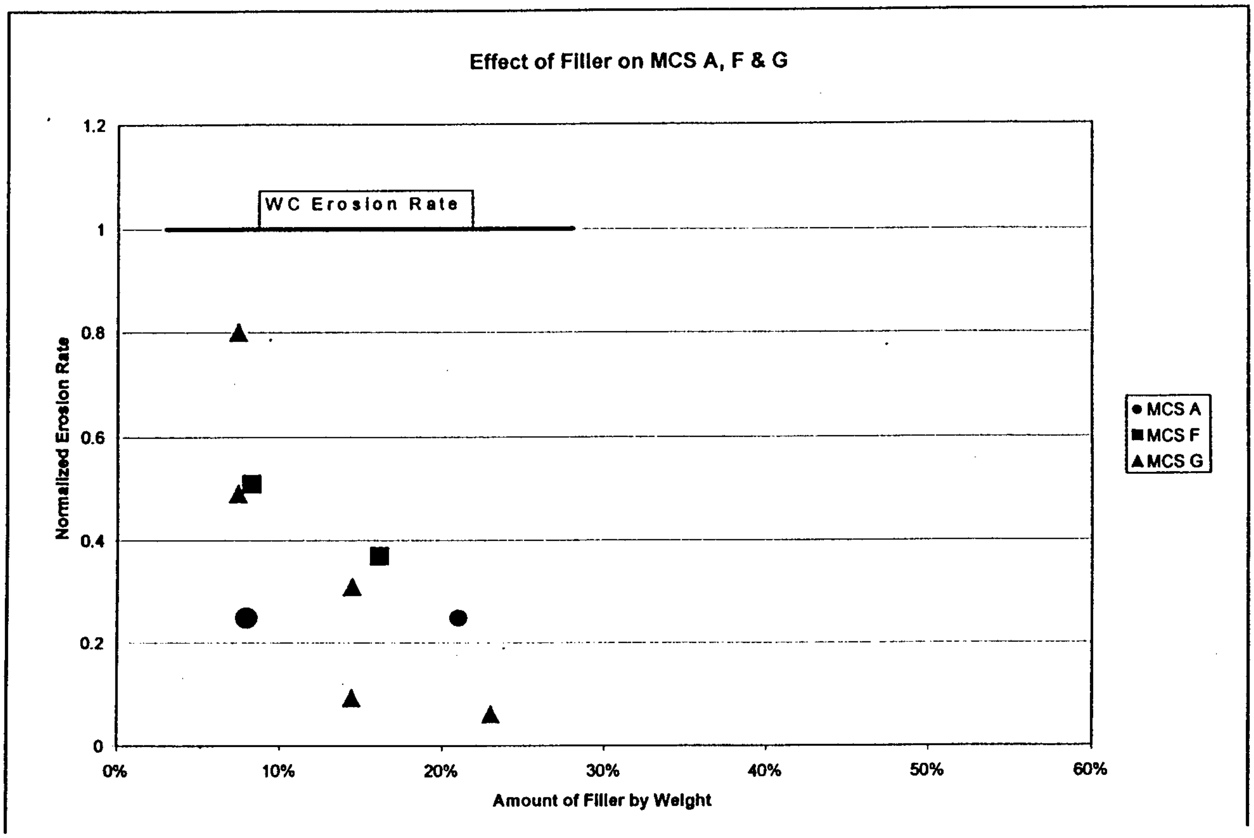

Fig. 9. Effect of filler on the erosion behavior of MCS coatings.